Children of the First Stars: Birth from a Population III Supernova?

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Abstract

We present a radiation hydrodynamics simulation to investigate triggered star formation following a supernova of a metal-free (Population III) star, possibly providing a direct connection between a single Population III star and a subset of extremely metal-poor stars. We simulate the formation and ensuing radiative and supernova feedback of several Population III stars in a cosmological volume with the adaptive mesh refinement code, Enzo. In the vicinity of one of the stars at redshift 15, the blastwave from a 10^{52} erg supernova passes a molecular cloud of mass 900 $M_\odot$. Existing only 9 pc from the star, the cloud survives the blast and is not completely photo-evaporated. After the star explodes, the blastwave rapidly shock-heats the diffuse gas, increasing the external pressure which could potentially crush the cloud into collapse. We study how metals propagate into the cloud, causing it to cool and possibly provide the seed for metal poor stars. 650 kyr after the supernova, the cloud nearly exceeds the Bonnor-Ebert mass suggesting might might continue to grow and collapse to form stars.

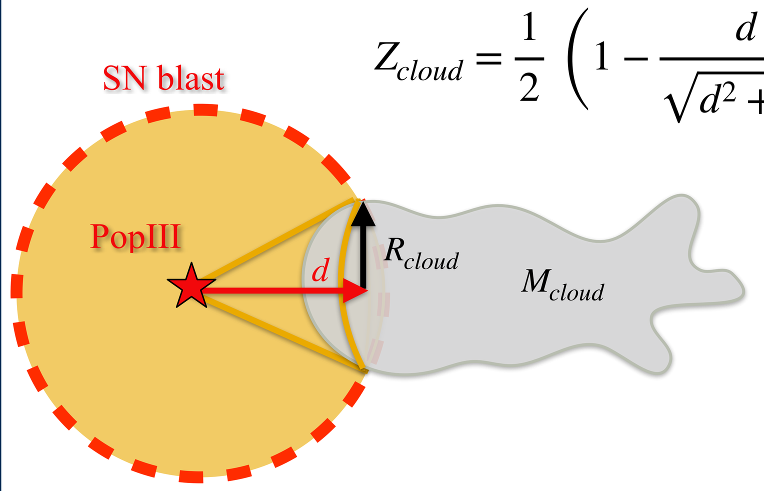
Introduction

The early universe was entirely devoid of metals only until the death of the first Population III stars. Then we begin to see metal enriched stars and galaxies. As metals allow gas to efficiently cool and fragment, understanding their origin and proliferation has important consequences for the evolution of the first stars and galaxies as well as structure formation.

Metal Enhancement Estimate

Assuming perfect metal mixing, that is if all the metals in a spherical cone whose base is the cross sectional diameter of the cloud get mixed in, then we can compute the metallicity of the cloud after the SN blast passes. If the Pop III star is a distance d from the cloud which has cross sectional radius R_{cloud}, and ejects a total metal mass of $M_{Z,SN}$, then the final metallicity of the cloud is

$$Z_{cloud} = \frac{1}{2}\left(1 - \frac{d}{\sqrt{d^2+R^2}}\right)\frac{M_{Z,SN}}{M_{cloud}}$$

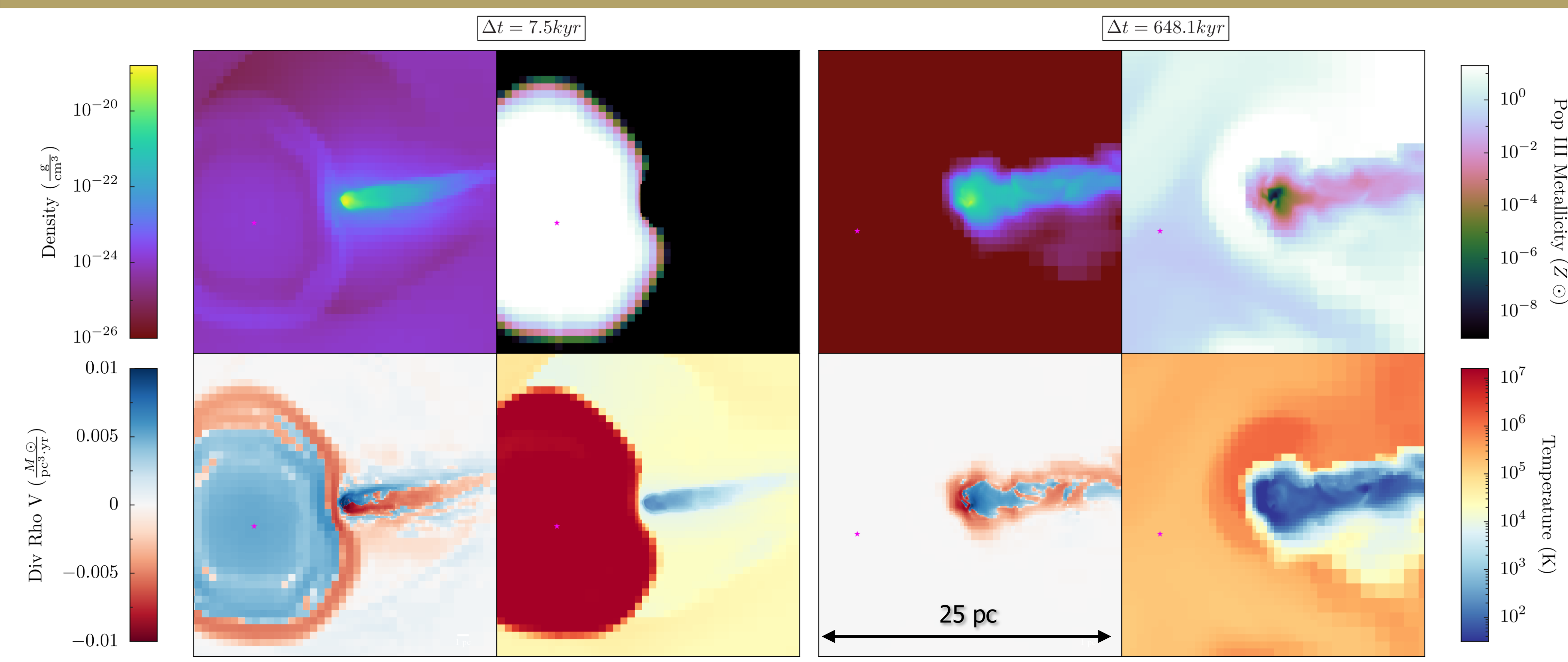


$M_{Z,SN} = 8.59\ M_\odot$ $\quad d = 8.7$ pc

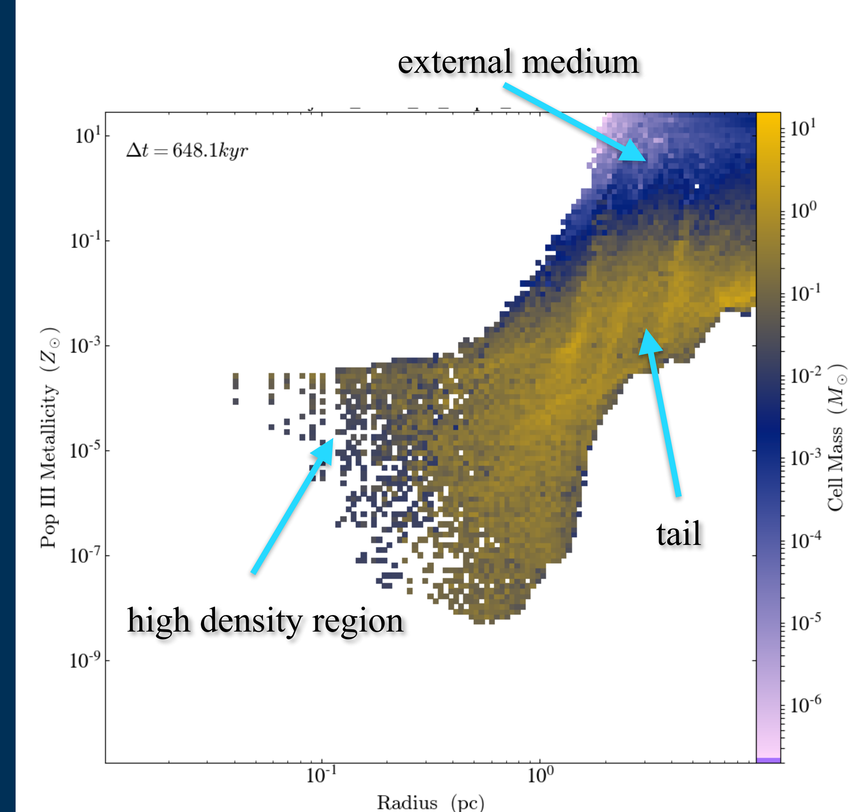
$M_{cloud} \approx 900\ M_\odot$ $\quad R \approx 2$ pc

$$\Longrightarrow Z_{cloud} \sim 2\times10^{-3}\ Z_\odot$$

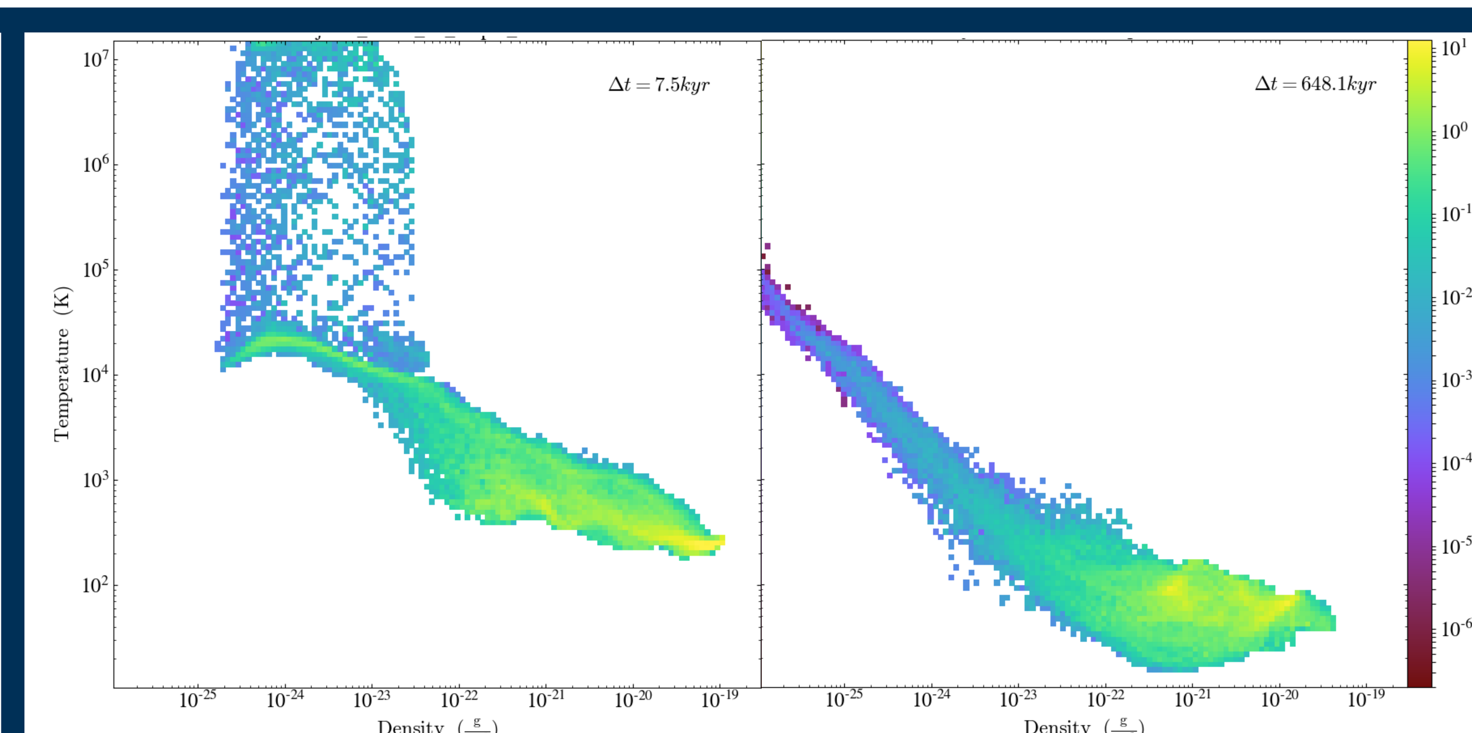
Results



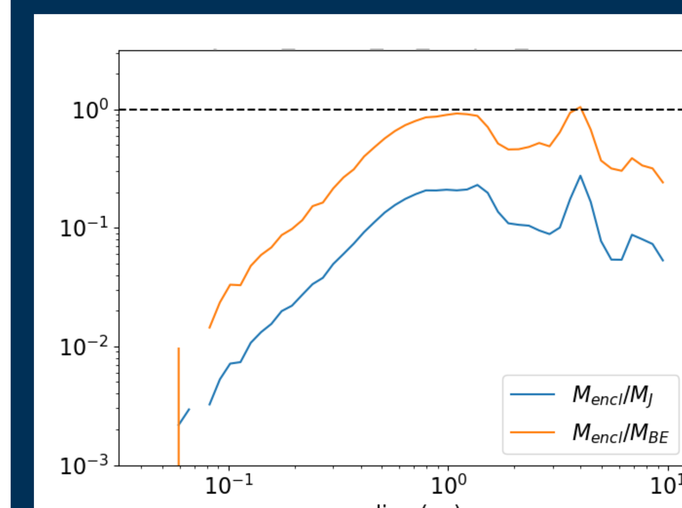
- Slice plots at the location of maximum density in two different snapshots.
- Left panels show the hot, metal enriched, supernova blastwave contacting the clump 7.5 kyr after the star explodes. Right panels show the state of the clump 648 kyr after the star explodes.
- The clump has grown in size, cooled an become metal enriched. However, the central region is still pristine.
- Mass is flowing onto the clump, however it has not collapsed to higher density.



- Phase plot showing the metallicity in a 10 parsec sphere centered at the point of maximum density in the clump.
- Approximately 650 kyr after the supernova, metals are still mixing into the clump raising its metallicity to a maximum around 10^{-3} $Z_\odot$.
- As the clump and surrounding ISM becomes metal enriched, the gas is a able to efficiently radiatively cool allowing the ambient medium to condense onto the cloud.

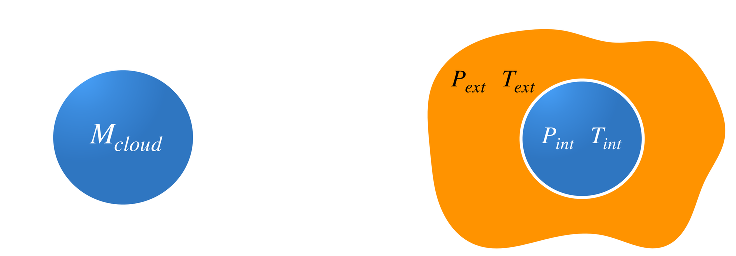


- Density and temperature phase plots from two different snapshots.
- The supernova rapidly heats the external medium then cools and condenses onto the clump.
- Maximum density remains around 10^{-19} g/cm³. This indicates the clump is not yet massive enough to become gravitationally unstable.



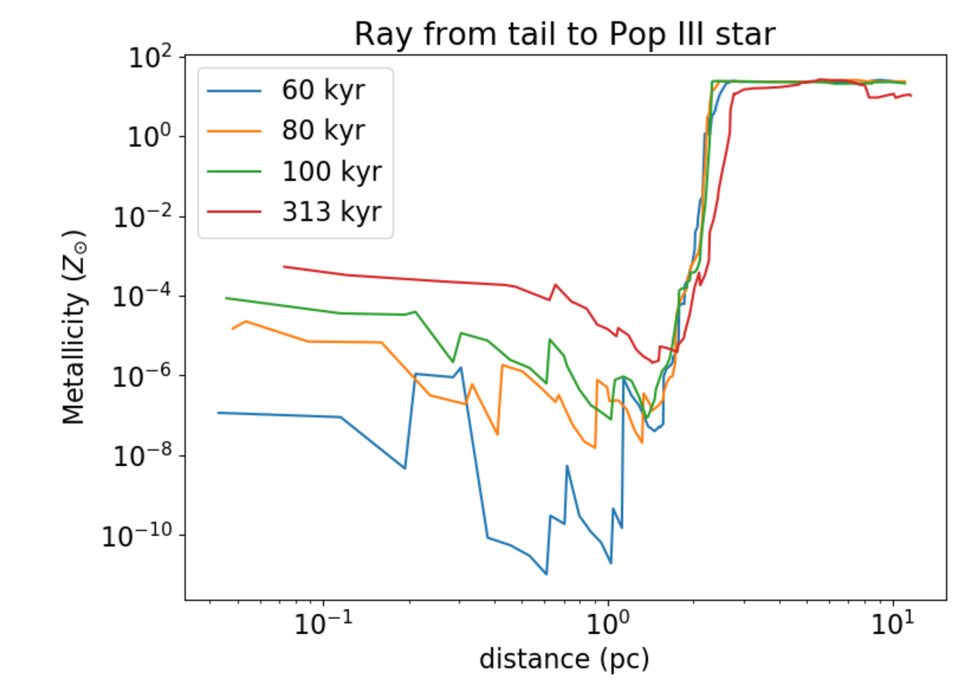
Critical Mass

$$M_J = \sqrt{\frac{3\pi^5}{32G^3\rho}}\,c_s^3 \qquad M_{BE} = 0.22\sqrt{\frac{P_{int}T_{int}}{P_{ext}T_{ext}}}\,M_J$$



Conclusions

Although it appears the supernova does not immediately trigger the collapse of the nearby cloud, this is still a valuable simulation for studying how metals from a Population III star enrich the ISM and initiate the transition to a metal enhanced universe.



- Gas metallicity along a ray from the tail of the clump to the Pop III star.
- Metals filter in raising the metallicity of the tail to about 10^{-4} $Z_\odot$ on a 100 kyr timescale.
- The mixing slows over the next 350 kyr reaching a metallicity close to 10^{-3} $Z_\odot$ 313 kyr after the supernova.
- The metallicity in the tail remains close to this value for the remaining 340 kyr of the simulation.

Future Work

This is ongoing work and the simulation and analysis is not yet completed. Even if the clump does not collapse in direct response to the supernova, there is still a chance it will form stars. 650 kyr after the explosion of the Pop III star, the velocity of the clump relative to its host dark matter halo is 64% the escape velocity of the halo which has a mass of 10^6 $M_\odot$. As the clump falls deeper into the halo's potential well, it may develop a gravitational instability. This would allow more time for metal mixing, ensuring the next generation stars are enriched with metals from the Pop III supernova.

In the simulation presented here, we resolve the local Jeans length by a minimum of 16 cells. We are also conducting a resolution study of three similar simulations where we resolve the Jeans length by a minimum of 8, 32, and 64 cells. We've yet to complete the analysis of these simulations but our preliminary results show that the 8, 16, and 32 resolution runs are nearly identical, while the 64 resolution run shows higher density and metallicity in the final snapshot.